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REINFORCEMENT OF HISTORIC MASONRY: THE "RETICOLATUS TECHNIQUE"

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SOMMARIO
Nel presente lavoro viene proposta una tecnica per il rinforzo di murature realizzate con elementi anche irregolari (ad esempio in pietrame), per le quali sia richiesto il mantenimento della caratteristica di faccia a vista. La tecnica consiste nell'inserimento nei giunti di malta di un reticolato continuo di piccoli trefoli in acciaio ad alta resistenza i cui nodi sono fissati mediante barre metalliche trasversali al paramento murario. La successiva ristilatura copre i trefoli e la testa delle barre trasversali. Il risultato finale dell'intervento è quello di una muratura armata per la quale si ha un incremento delle caratteristiche meccaniche (resistenza a compressione, a taglio e a flessione), un efficace collegamento tra gli elementi murari contigui ed anche tra i paramenti della muratura, se vengono utilizzati adeguati connettori trasversali. L'intervento che si propone come integrativo delle altre possibili tecniche, risulta sostanzialmente reversibile, inteso a rinforzare la muratura attraverso un presidio e non a sostituirla, compatibile con la conservazione materica del manufatto e durevole. Varie sperimentazioni, qui presentate, hanno dimostrato in modo convincente l'efficacia strutturale della tecnica in questione.

ABSTRACT
A new technique is proposed for reinforcing rubble stone masonry walls (double and triple-leaf walls), when the fair-face masonry must be kept. The reinforcement technique consists of embedding a continuous mesh of high strength steel cords in the mortar joints after a first repointing, and then anchoring this to the wall by means of transversal steel bars. A second repointing covers the cords and the heads of the steel bars. This gives a reinforced fair-face masonry wall in which there is increased compression, shear and flexural strength, an effective transverse connection between the masonry leaves due to the presence of the steel bars, and the capacity to withstand tensile stresses, as was confirmed by the first tests. The reinforcement is non-invasive and reversible, and is aimed at integrating the masonry rather than transforming it. Various experimental tests, briefly presented here, have clearly demonstrated the structural effectiveness of this technique.

1. INTRODUCTION

The consolidation and strengthening of masonry walls that are subjected not only to their own weight but also to possible dynamic stresses constitute one of the most important reinforcement works for achieving an adequate level of safety.
This is because poor quality in the mechanical characteristics of the masonry (compressive strength, shear strength, etc.), especially in old historic buildings, has often been the cause of collapsing or of serious damage, for example during seismic events.
Another element that has a considerable impact on the seismic behaviour of a masonry construction is the connection between vertical walls and between these and the horizontal elements. If these connections are present and effective, they can allow the structure to respond adequately to dynamic stress by means of a “box-like” behaviour, without a loss of balance in the individual sections. If these connections are lacking, each individual element (a wall, floor slab, etc.) will be more vulnerable, since it will be free to collapse separately from the rest of the construction.
The techniques used for restoring or reinforcing masonry structures, such as the “scuci-cuci” (patching) of the masonry, the repairing of cracks by means of perforations reinforced with metal bars, circling with strips of composite material, injection into the masonry of cement grout or lime-based mixtures, reinforced plaster, etc., present some limits and problems. This is especially true in the case of irregular masonry in which it is desired to keep the exterior facing unaltered.
The technique of the deep repointing of the mortar joints that consists of stripping the joints in the masonry by removing the original poor-quality mortar and then repointing the joints with a good quality mortar can be used when the fair-face masonry must be kept. Its effectiveness, however, is limited as regards the increase in the mechanical properties of the masonry, especially if the walls are very thick.
This paper describes a new reinforcement system, called “reticolatus,” which is proposed separately or in addition to other techniques (such as injections) and it allows the reinforcement of both regular and irregular masonry, with a limited impact.
As is demonstrated in the experiments presented below, it can make important contributions as regards both horizontal stresses, such as those caused by earthquakes, as well as static vertical loads.

2. DESCRIPTION OF THE RETICOLATUS TECHNIQUE

The reinforcement system consists of a continuous mesh of tiny cords made of high strength steel (brass coated or galvanized with zinc, for greater protection against corrosion), which are inserted into the mortar joints and thus embedded in the wall.

2.1. Materials

The system is based on the use of following materials:
a) High strength steel cords, which can be made from coils found on the market. The coils vary in length from 15 m up to 1500 m, and consist of a series of cords laid out parallel to each other and held together by a polyester mesh. It is easy to detach the steel cords out from the strip so as to use them separately. The specifications of the single cord 3x2 are shown in Table 1. In the case of lime-based mortars, as mentioned, the zinc galvanized type can be used, or other materials may also be used, such as composite materials, provided it is possible to use a cement or lime-based mortar as a matrix.

Fiber type	3X2
Cross section area (mm^2)	0.481
Failure tensile load (N)	1539
Density (g/m)	18.45
Elongation at failure (%)	1.6

Tabella 1. 3X2 cord properties.

b) galvanized steel bars threaded at the ends, which, along with a nut, washer and “cord locking device” (Figure 1), make it possible to hold the cord inside the mortar joint.
The most interesting property of the cords used in the proposed system is the fact that their very small size (typical average diameter 1 mm) and their shape, formed by wrapping the individual steel filaments around each other helically (typically 3 or 4 filaments) give rise to high bonding and compatibility between the cords and the mortar surrounding them. This ensures excellent mechanical behavior of the “stone-mortar-cord” assembly. Furthermore, because the cords are so small, they can be easily bent into shape as required in order to pass them through the joints between the various pieces of stone forming the wall (Figure 2).

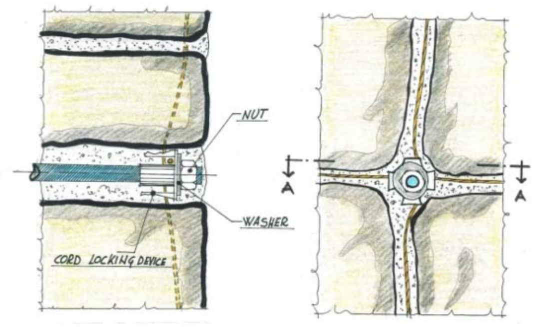


Figure 1. Close-up of hooking system

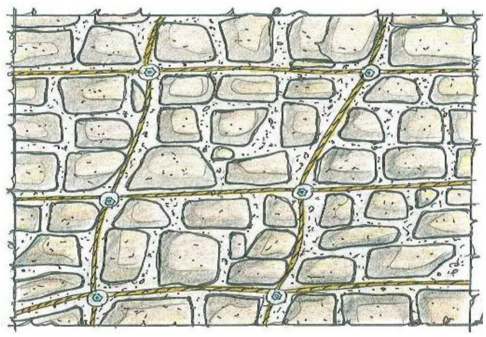


Figure 2. A typical continuous mesh

As concerns the chemical compatibility of the above materials, a number of corrosion tests were carried out which provided positive results, even in particularly aggressive environments. When lime-based mortar is utilized for repointing, it is best to use steel protected by zinc galvanizing or else composite material cords (aramid fibers); metallic cords can also be used if suitable protection (e.g. a plastic sheath or spray coating) is applied beforehand. For this type of application the adhesion between cord and matrix is not fundamentally important, it being possible to count on a mechanism of mutual confinement between the mesh and the stone.

2.2. Application of the reticolatus

The application is done in the following stages:

- strip the mortar joints in the wall to a depth of 6-8 cm, being careful not to remove the original mortar where it is particularly strong;
- hydroblasting of the stripped joints, doing this operation a few hours before the subsequent application of mortar;
- inserting of the transverse elements (threaded galvanized steel bars, complete with nut, washer and cord locking device). They are typically placed in a minimum number of 4

per square meter, in meshes evenly spaced when it is possible. The anchoring depth of the bars depends on the quality of the masonry: in the case of good quality masonry (with transverse bonding), a depth of 15-20 cm is sufficient (Figure 3); with poor quality masonry, the anchoring depth should be at least 2/3 of the wall thickness (Figure 4a); or, in the case of walls built with small pieces of stone, the anchoring can pass entirely through the wall, thus creating a complete and direct connection between the meshes of the two faces (Figure 4b);

- fixing of the bars to the wall using specific non-shrink mortars or epoxy resins;
- first repointing with mortar;
- insertion of the UHTSS cords into the stripped joints, passing them through the cord locking devices, proceeding horizontally or vertically across the entire facing being reinforced. If the individual cords are not long enough, they can be joined with resin or simply overlapped with each other by about 20 cm (Figure 5);
- if considered necessary additional cords can be applied diagonally in both directions;
- tightening of the nuts to lightly tension the cords;
- second repointing of the mortar in the joints, completely covering both the cords and the heads of the eyebolts or bars;
- aesthetic finishing of the joints by brushing them with a metal brush.

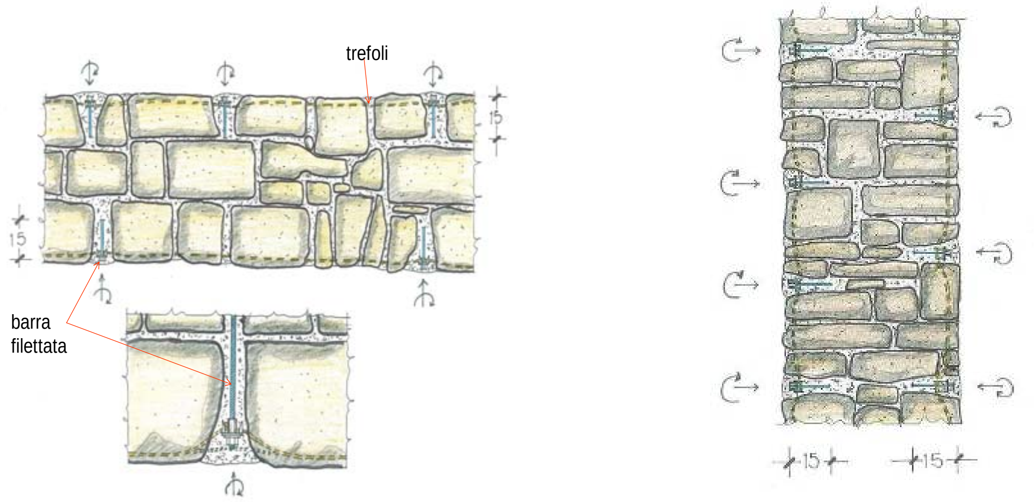
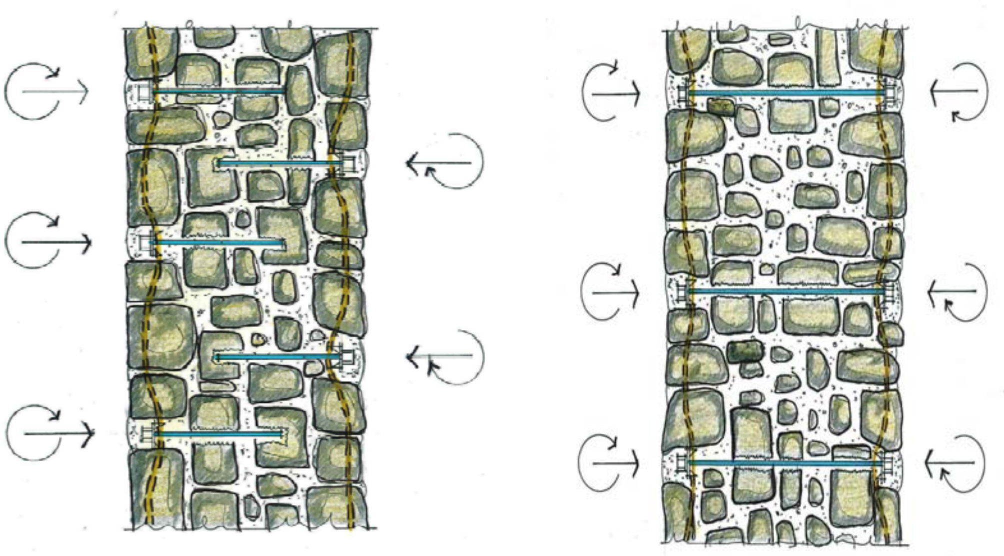


Figure 3. “Reticolatus” reinforcement work for good quality masonry (with transverse bonding).

In the case of poor quality masonry (e.g. rubble work, with mortar having poor mechanical properties and without transverse bonding elements), the system must be accompanied by injection work that can give the masonry the necessary consistency.

From a mechanical perspective, the benefits that can be expected are: improved mechanical characteristics (both compression and shear strength, as well as flexural strength for loads both in and out of the plane of the masonry panel), the ability to extensively connect the vertical walls to one another and the vertical walls to the horizontal elements, the possibility of giving the masonry tensile strength, transverse connections between the facings of the masonry.

The system proposed can be used either locally, for example on single wall panels in existing structures (boundary walls, city walls, etc.), or overall, i.e. as a reinforcement system for a masonry construction for improving the overall behavior of entire buildings, especially as regards structural behavior during earthquakes.



a) b)

Figure 4: “Reticolatus” reinforcement work for poor quality masonry: vertical section.
a) bars passing partially through; b) bars passing completely partially through.

Figure 5: Picture of the cords into the joints

3. TESTS

In order to investigate the effectiveness of the proposed reinforcement technique, three different series of tests were planned: compression tests using two flat jacks, diagonal tests and flexural tests.

3.1. Compression tests

The compression tests were carried out on the city walls of Trevi (Perugia–Italy). Masonry portions of walls about 50 cm thick were tested by being subjected to compression on a single vertical axis using two flat jacks. During the test the values of the applied pressure and the deflection of the masonry were recorded at each load step. These values were processed to

give the stress-strain diagrams (Figure 6), from which the compression resistance and Young's modulus calculated at 33% of the maximum stress were determined.
The results shown in Table 2 and in Figure 6, regard: the unreinforced masonry (URM), the deep repointed masonry (REP) and the masonry reinforced with the reticolatus technique (SRE). Upon analysis of the results, it can be stated that the reticolatus technique is able to increase significantly the compressive strength σ_{max} of the masonry: a mean value of 1.29 MPa was measured, corresponding to an increase of compression strength of 116% compared to the unreinforced panels (σ_{max} = 0.595 MPa). Furthermore, the mean increase of the masonry reinforced with repointing alone (σ_{max} = 0.834 MPa) is about 40% compared to unreinforced panel.
As concerns the failure mechanism, it was seen that a series of vertical cracks formed between the two flat jacks. Furthermore, there was no substantial differentiation of the type of failure between the unreinforced masonry, the repointed masonry and the masonry reinforced with metal fibers. Whereas in the cases of the unreinforced masonry and of the repointed joints the failure occurred with a small number of fairly large vertical cracks, in the case of reticolatus reinforced masonry a larger number of smaller vertical cracks occurred, indicating an improvement in the mechanical behavior of the masonry due to a probable decrease in the concentration of the maximum stresses within the masonry.

	Max compression stress σ_{max} (MPa)	Young's modulus $E_{1/3}$ (MPa)
URM 01	0.595	480
REP 02	0.807	393
REP 03	0.857	512
SRE 04	1.261	486
SRE 05	1.312	2416

Tabella 2. Results of the tests with double flat jacks

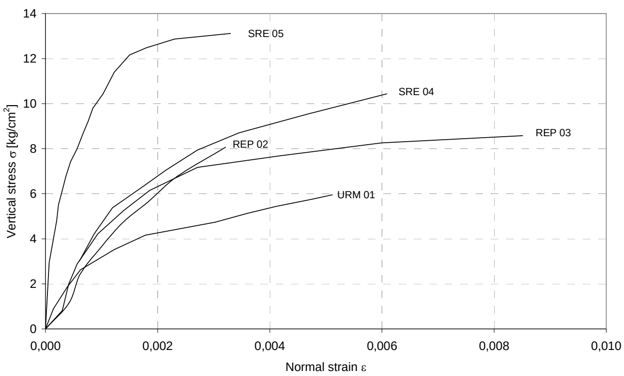


Figure 6. Diagram (σ-ε) resulting from the tests with double flat jacks

3.2. Shear tests

The diagonal compression test defined by the ASTM E 519-81 Standard was designed in order to evaluate the effectiveness of the reinforcement as regards shear stress. The tests were performed on site on three stone masonry panels cut from a 17th century building in Pale, near Foligno (Perugia-Italy).
The panels, having a thickness of 53 cm and consisting of very roughly hewn stone (travertine and compact limestones) and lime-based mortar with weak mechanical properties, were consisted of two weakly toothed facings without cross blocks.
The panels were cut to a size of 120x120 cm, and a series of metal beams were then applied at the two edges of one of the two diagonals of the panel, connected by bars. A jack was applied at one of the edges in order to stress the panel until it failed along one of the two diagonals.
The diagonals on both faces of the panel were instrumented with two inductive displacement transducers. During testing the load applied and the variation in the length of the diagonals were recorded (Figure 7).

Figure 7. The diagonal compression tests

The results expressed in terms of shear strength τ_k and of shear elastic modulus $G_{1/2}$ are shown in Table 3 and in Figure 8 (τ-γ diagrams), from which it can be seen that the different reinforced techniques (deep repointing of mortar joints or "reticolatus") applied have greatly increased the strength.

In particular, the "reticolatus" and the deep repointing show an increase in the shear strength of 117% and 35% respectively, compared to an unreinforced panel. Thus it can be noted that for τ_k a percentage increase is obtained that is similar to that reported for the compression strength in the preceding series of tests. The increases in the shear elastic modulus $G_{1/2}$, calculated in this case at ½ of the shear strength of the masonry, were less significant: in the case of the "reticolatus" a value of 653 MPa was obtained, compared to the value of 541 MPa for unreinforced masonry.

	Max shear stress τ_k (MPa)	Shear elastic modulus $G_{1/2}$ (MPa)
DC01 Unreinforced	0.029	541
DC02 – Deep repointing	0.039	1403
DC03 Reticolatus	0.063	653

Tabella 3. Results of diagonal compression tests

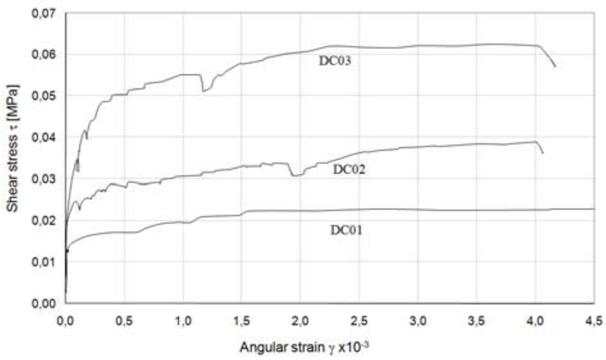


Figure 8. Diagram (τ-γ) resulting from the diagonal compression tests

3.3. Flexural tests

In order to investigate the effectiveness of the reinforcement system proposed, a new experimental test was conducted, building two rubble stone wall panels reinforced using the "reticolatus" technique.

The two panels were then rotated and placed horizontally, thus subjecting them to a particularly severe flexural test, given the great weight of this wall type.

The panels were built with rough-hewn limestone rubble coming from the demolition of existing walls and cement-lime mortar with modest mechanical properties. The panels are made up of two facings, one (panel 1) without any headers, and the other (panel 2) weakly toothed. Once they had set, the two panels were reinforced with the "reticolatus" technique, using the same 3x2 cords manufactured by Hardwire LLC used previously, according to the stages previous described.
In the first panel, built to investigate the flexural behavior (dimensions: 50 x 268 x 100 cm), in the longitudinal direction 24 cords/meter were applied to the intrados and 12 cords/meter to the extrados, whereas in the transversal direction 24 cords/meter were inserted, for a total of 324 cords applied (Figure 9).

Figure 9. Panel 1: front and side views

The second panel, built to investigate the shear behavior (40 x 180 x 198 cm), was reinforced in a manner similar to the first panel, again with 12 cords/m on both faces and in both directions, and integrating the face that will be on the inside with an equal number of cords, thus obtaining 24 cords/meter in the two directions on the intrados and 12 cords/meter in the two directions on the extrados, for a total of 175 cords applied (Figure 10).

Figure 10. The second panel subjected to flexural tests

Repointing was done on both panels with cement-lime mortar with modest mechanical properties, with an average depth of about 7 cm. The cords were inserted at a depth of 3-4 cm. The first panel was placed on a horizontal plane, supporting it at the ends. The four-point bending test was done, with a span of 208 cm and with the loads spaced 38 cm apart (Fig. 11). The panel was stressed by its own weight (calculable at 2200 Kg/m^3) as well as by the application of a load increased by increments of 150 kg, distributed among the two loading devices. The displacement was measured by six centesimal comparators placed on both sides of the panel, at midpoint, ¼ and ¾ of the span. The panel reached a critical situation with a load of about 600 kg, corresponding to a maximum flexural moment of 255 kgm, which are added to the 595 kgm deriving from its own weight.

Figure 11. Panel 1, placed horizontally, on two supports

As regards the panel failure mode, various observations can be made. Some cracks parallel to the supports opened in the tension zone, starting with the third load step (450 kg), and these cracks widened progressively up to the 650 kg load, when, due to the deformation of the intrados, some pieces of the intrados contained inside the mesh of the “reticolatus” fell by gravity, and then the masonry itself crumbled apart (Figure 12).
In comparison with a situation of an evenly distributed load equivalent to that applied in the case being examined, the panel failed with a uniform load (inclusive of its own weight) of 1610 kg/m.

Figure 12. Failure of panel 1

The second panel (40 x 180 x 198 cm) was also subjected to a four-point bending flexural test. In this case the panel was significantly shorter and wider than the first panel. The load,

almost entirely concentrated in the middle, has a punching effect on the panel that mobilizes mainly the out-of-plane shear resistance.
The panel was tested over a span of 124 cm (along the 180 cm side), and the load was applied by means of two HEA metal beams spaced 35 cm apart, with loads increasing by steps of 100 kg (Figure 13).
The test results seem especially significant for the purposes of demonstrating the effectiveness of the reinforcement technique proposed. Indeed, the panel did not reach the failure point, even though a load of about 2000 kg was applied, corresponding to an equivalent uniform load (inclusive of its own weight) of 4100 kg/m.
The panel was not brought to the collapsing point so that it could be used in a subsequent test.

Figure 13. Testing of panel 2

The two experimental tests described above gave excellent results, considering that the panels were tested by placing them horizontally and subjecting them to flexure, a very difficult situation for structures of this type.
A preliminary evaluation of the failure loads, based on the simplified flexural checking of the two reinforced structures, and considering, for simplicity's sake, the cords as being arranged parallel in the direction of the flexural stress (i.e. as if it were a reinforced masonry beam), it would have provided values of about 1800 kg for panel 1 and 8000 kg for panel 2, assuming a typical average value for the compression strength of the masonry for the type in question.
These values correspond, however, to failure due to tensile stress of the cords in the tension area, a mechanism that was not reached for the case examined (panel 1) because it was anticipated by the falling of pieces and crumbling of the masonry at the intrados.
The crumbling of the masonry in the tension zone was also facilitated in this particular situation (masonry placed horizontally) by the rather large size of the blocks, which "hang" from the intrados and thus tend to fall downward, sliding along the mortar joints, facilitated by their weight. In real situations, with the wall set vertically, the behavior is obviously much different, given than its own weight acts in the plane of the panel.

4. DESIGN

The results of the experiment showed the necessity of finding a model that can describe, in a manner consistent with the real situation, the mechanical behavior of the masonry reinforced using the reticolatus technique.
Diverse methods, from the simplest to the most sophisticated, are being tried regarding this aspect.
It should be said however that in works in which all that is proposed is an overall improvement of the performance of the masonry, some suggestions of a qualitative type will be sufficient, deriving from the experiments done and from the comparison with the RC jacket technique, which, although entirely different, does have some similarities with the proposed technique. Indeed, the RC jacket technique consists of two separated reinforced concrete thin walls, external to the existing walls. In case of the proposed technique, definitely there are no reinforced concrete facing walls but improved face shell reinforced masonry walls, enabling much better continuity and compatibility with the existing material.
Following this analogy, the minimum number of nodes in the mesh must not be less than 4/sq.m. and the area of the cords in the single side of the mesh must not be less than 19.60 sq.mm. per meter.
When a very precise strength increment is required instead, the mesh size and the size of the cords must be determined by means of a structural analysis that considers in a precise manner the different project requirements (flexure, shear, sliding). The analysis method is omitted here for the sake of brevity; let it suffice to say that in the two improved face shell reinforced masonry walls the cords work under tension and the masonry confined inside the mesh can work under compression. Various models can be followed, from a Morsch-type design to an FEM model in a nonlinear field.

5. CONCLUSIONS

The result of the presented technique is that of a reinforced masonry, for which there is an increase in compressive and shear strength. The improvement does not concern solely the mechanical characteristics of the masonry thus reinforced, but affects the entire masonry construction, since in addition to reinforcing the wall panel, the “skeleton” of the continuous grid inside the masonry connects the various contiguous masonry walls to one another, thus forming a reinforcement system. Furthermore, the small size of the reinforcement cords and the fact that they are easy to insert into the mortar joints makes it possible to apply this technique on an extensive, which avoids dangerous concentrations of stress.
The upgrading work is not very invasive and is reversible. It is compatible with preservation of the original material of the building and is therefore particularly suitable for fair-face walls of buildings registered as being of historical and/or architectural interest. Therefore historical and archeological buildings and structures may find the system proposed to be an appropriate solution for some of their structural problems, as it is able to combine the need to obtain high safety levels with the demands of protection and preservation.

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